NO. 4

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INLAND DC DIRECT-DRIVE TORQUE MOTORS FOR DYNAMIC POSITIONING IN . . .

DIGITAL TAPE TRANSPORTS

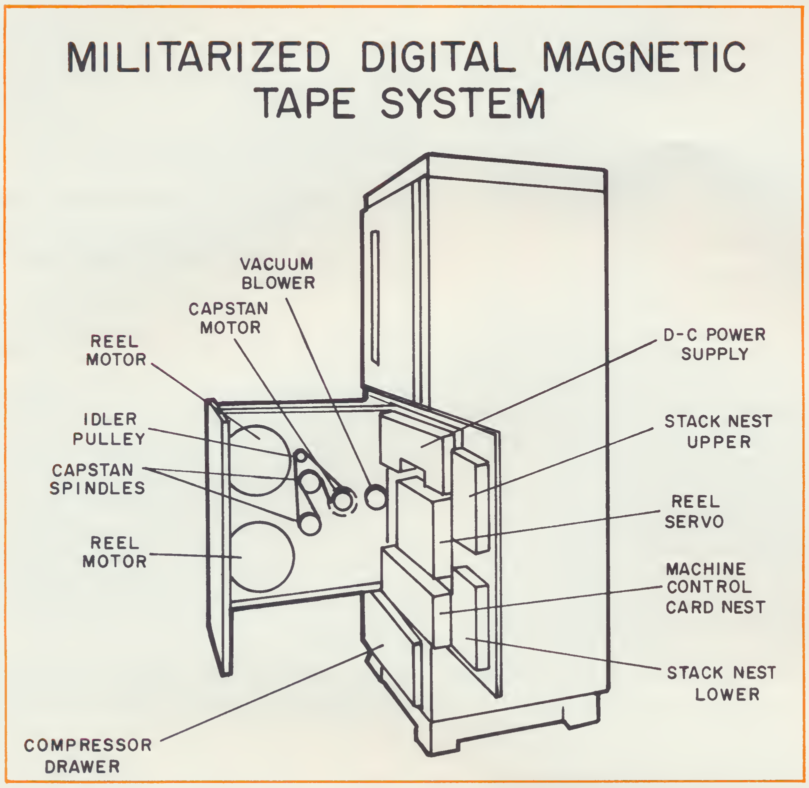

Figure 1.

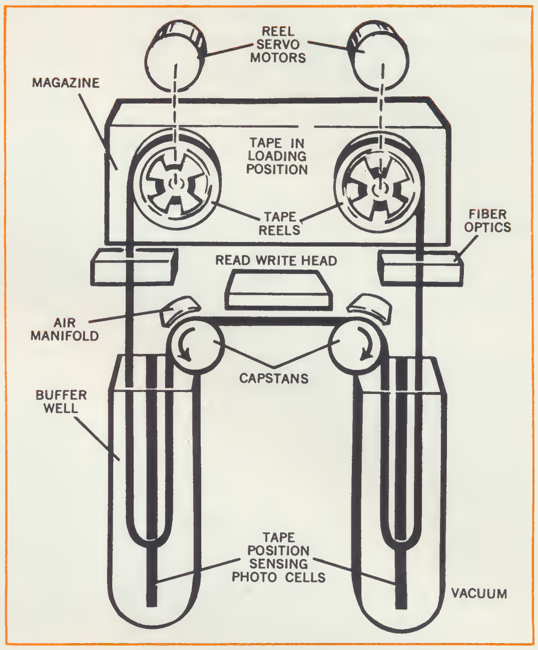

Figure 2.

One of the most critical areas in data processing is the design of tape handling equipment. These design requirements become particularly severe in militarized equipment. Sylvania's Electronic Systems Division of General Telephone Company, after extensive evaluation of other methods, found that only Inland DC direct drive-torque motors and tach generators provided the performance necessary to meet the unique requirements of MOBIDIC, the Army's mobile digital computor, shown in Figure 1.

The most important single feature of this tape transport is its capability for unrestricted computer programming. To accomplish this requires that the transport start, stop, and reverse on command from the computer with minimum response time and without causing damage or distortion of the magnetic tape. Typically, start and stop time is less than 3 milliseconds and complete reversal is less than 6 milliseconds over a dynamic range of 150:1.

In the following paragraphs, you will see how size, performance, and environmental limitations preclude the use of conventional, commercial tape transports and how the INLAND DC direct-drive ***dynamic positioning*** system provides significant advantages in implementing this unique design.

SYSTEM CONFIGURATION

For clarity, a simplified schematic of the digital tape handler is shown in Figure 2. Two constant speed counter-rotating capstans are used to drive the tape. These capstans may be operated at one of two speeds having a ratio of 150/1. The tape is applied to one of the two capstans by pneumatic pressure, using manifolds which are located directly above each capstan. Thus tape direction is determined by which capstan is driving, and tape speed is determined by capstan speed. With the exception of the magnetic head, no contact is made on the oxide portion of

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the tape. Also, to prevent tape damage the transport is cartridge loaded and self-threading. Vacuum buffer wells are used to tension the tape between the reels and the capstan.

DESIGN CONSIDERATIONS

Many commercial machines use buffer wells to handle the tape; however, the length of these wells is usually about 3 feet. With such a well depth a relatively simple position servo can be used on each reel motor to control the amount of tape that must be let off or taken up. With the tape operating theoretically at the middle of the well, approximately 18 inches of well depth is available to handle sudden speed changes, such as starts, stops, or reversals. In this militarized version, however, miniaturization of the transport reduced the total well depth to approximately 10 inches (more than a factor of three). Yet when this transport is handling 45,000 characters per second, the tape speed is 100 inches per second.

Reel speeds at 100 in/sec linear tape speed on this transport are 580 rpm on the empty reel and 250 rpm on the full reel. The safe linear acceleration that the tape can withstand is approximately 1000 inches/sec^2. When converted to the reels, this acceleration becomes approximately 570 rad/sec^2 on the empty reel and approximately 270 rad/sec^2 on the full reel. Any significant deviation from these values would cause overshoot, undershoot, or slippage of the tape on the reel, any of which could cause tape damage.

This combination of high tape speed (100 inches/sec), short buffer well depth (10 inches), limited acceptable tape acceleration and rapid tape reversal (6 milliseconds) to permit unrestricted programming introduced severe problems. Sylvania determined that the bandwidth of this system must be 300 rad/sec. To meet this, the damping in a position servo alone would be inadequate and a velocity servo must be added to extend the bandwidth.

Therefore, one of the first considerations was to select a reel drive means that would provide the necessary response time, have a readily controllable acceleration, be capable of operating over a 150/1 speed range, use a minimum of power, be as light and small as possible, and satisfy the maintenance requirements. This must be performed without resorting to excessively complex electronic or mechanical means.

MOTOR SELECTION

Geared servo motors, whether AC or DC, could possibly be used, but to attain controlled acceleration with the relatively large amount of stored energy in the rotor, they would have to be pushed beyond their ratings. This would require excessive power, and the resultant heating could be absorbed on the reels causing tape stretch and distortion of data. Also to cover this wide speed range, electronics became complex. The regenerative capabilities of an AC motor are insignificant and offer no dynamic braking possibilities. This is a most desirable feature of DC machines which is employed in this case to assist in quick reversal of the tape reels.

A continuously running synchronous motor with magnetic clutches was actually tried. The response time of the magnetic clutch reduced servo bandwidth and restricted programming. Other objections to this type of drive were heat dissipation in the clutch and relatively high power requirements.

INLAND'S standard Model TT-4005, a tachometer generator - torque motor combination, shown in Figure 3, was evaluated and found to surpass these performance requirements. The torque motor section shown on the left directly drives the tape reels. The tachometer generator on the right generates the voltage to increase damping. Featuring a peak torque output of 3.5 lb.-ft., this compact, completely housed unit weighs only 12 pounds and is capable of operating at speeds well in excess of the maximum rewind speed of 1200 rpm.

The performance characteristics are listed in Table 1. Also included are some of the pertinent requirements for the reel drive.

MOTOR PARAMETERS

Since acceleration is the ratio of torque to total inertia, the torque required for an acceleration of 570 rad/sec^2 (empty reel) is 570 x 2.6 = 1.5 lb. ft. For the full reel it is 270 x 5.5 = 1.5 lb. ft., also. Therefore, this motor was designed to have a continuous rating at this torque level. Peak acceleration capability of motor is more than twice acceptable limit.

Torque sensitivity is the ratio of torque to current. It is given in Table 1, as 0.23

TABLE 1.

TACH-TORQUER TT4005A CHARACTERISTICS

TORQUE MOTOR PERFORMANCE	
PEAK TORQUE (STALL)	3.5 lb-ft
VOLTS @ STALL 0.25°C	9.0 volts
CURRENT @ STALL	15.0 amps
POWER @ STALL 0.25°C (I^2R)	135 watts
TORQUE SENSITIVITY	0.23 lb-ft/amp
BACK EMF GRADIENT	0.31 volts/rad/sec
VISCOUS DAMPING	0.12 lb-ft/rad/sec
TOTAL ROTOR INERTIA	1.8 x 10^{-3} lb-ft sec^3
INHERENT ACCELERATION	1944 rad/sec^3

TACHOMETER-GENERATOR PERFORMANCE	
VOLTAGE GRADIENT	0.31 volts/rad/sec
GENERATED VOLTAGE	41 volts @ 1300 rpm
	20 volts @ 640 rpm
	9 volts @ 280 rpm
	135 millivolts @ 4.3 rpm
	60 millivolts @ 1.9 rpm
	63 volts @ 2000 rpm*
INERTIAS	
ROTOR	1.8 x 10^{-3} lb-ft/sec^2
TOTAL ROTOR PLUS REEL (EMPTY REEL)	2.6 x 10^{-3} lb-ft/sec^2
TOTAL ROTOR PLUS REEL (FULL REEL)	5.5 x 10^{-3} lb-ft/sec^2

*MAXIMUM OPERATED SPEED

ACCELERATION RAD/SEC^2 (T/J)

	REQUIRED	MOTOR CAPABILITY
EMPTY REEL	570	1350
FULL REEL	270	635

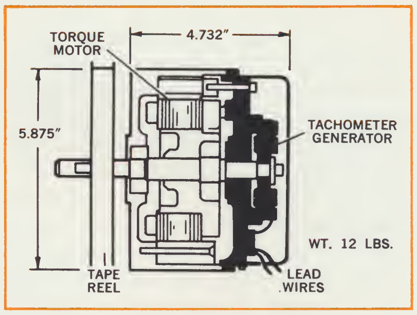

Figure 3.

lb. ft./amp. Dividing the torque by the current at peak rated value or at the continuous rating shows the value to be the same. Hence, within the motor, rating sensitivity is constant and independent of speed. Thus we have a true torque current transducer. Since the acceleration is a function of torque, it can readily be limited by controlling the current into the motor. This feature is used in this application to protect the tape.

The back emf or voltage gradient is directly related to the torque sensitivity and likewise is constant. The fact that the sensitivity is constant implies that armature reaction has insignificant effect. The motor speed may be readily calculated by subtracting the voltage drop in the rotor (caused by the flow of current through the rotor resistance) from the terminal voltage and dividing the result by the back emf. The speed torque curve for any applied voltage is a straight line. Hence, as long as the peak rated current of the motor is not exceeded, which would produce excessive armature reaction, and the applied voltage does not exceed a safe value and cause arcing on the commutator, the speed of the motor can be simply controlled.

Figure 4 (A) shows a family of curves for this motor with various arbitrarily chosen voltages applied to the terminals. To cover the speed range encountered in this particular application note that the speed torque characteristic is a straight line, the curves are parallel, and approximately proportional to the applied voltage.

Note also that while the projection of these curves above 9 volts would go well beyond the 3.5 lb. ft. of torque, it is limited to the peak rated torque at all times so that it operates in the linear region of the motor characteristic only. The current is also a straight line. As mentioned previously, it is constant for any value of torque and independent of speed. These linear characteristics simplify servo design.

Figure 4 (B) merely cross-plots A to show a typical characteristic that would be expected if the voltage were to drop linearly with increasing torque.

In the electronics developed by Sylvania, the characteristics of the torquer and the tach-generator are put to use. We would like to refer back to Figure 3 for a moment to discuss some features purposely not discussed earlier. If the tape was in the mid-position of the well during operation, at a sudden change in tape speed resulting from a computer command, such as to reverse, it would be necessary to apply twice the acceleration to the tape as is permissible to keep the tape in the well. While the motor has twice the acceleration capability, tape damage would result. Therefore, in order to minimize acceleration, Sylvania biased the tape such that the tape being fed into the machine is operating near to the top of the well and the tape being taken out of the machine is operating near the bottom of the well.

As mentioned before this, the transport must be self-threading. During the first phase of the operation when the start button is pushed, the reel motors operate in open loop. With a low voltage (approximately 2 volts) applied, the tape is played off the reel at approximately 65 rpm. Here speed is limited by the back emf of the motor as described above. Through the electronic controls, the motors are operated in the proper sequence to thread the tape into the machine and then stop until it gets a command signal from the computer.

DYNAMIC POSITIONING CONTROL

Referring to Figure 5 the reel speed is slaved to the rate of feed of tape from the capstan, through the position loop, which is the only error sensing in the system. The error signal is obtained from a series of 26 photocells spaced along the buffer well. With the electronics biased to position the tape as described, any change in tape position in the well creates an error signal which appears at the summing point "A". The resulting voltage is fed into the summing point "B". Here the rate loop provides the necessary additional control.

It is important to remember that the tape is operating at a constant speed controlled by the capstan. Due to the short buffer well depth, the tape reel drives not only must let off and take up tape at the proper rate so the tape remains in the buffer wells, but also they must maintain a discrete position in the wells. However, the tape reel diameters are varying constantly as tape is fed through the transport. The tach-generator being driven by the reel

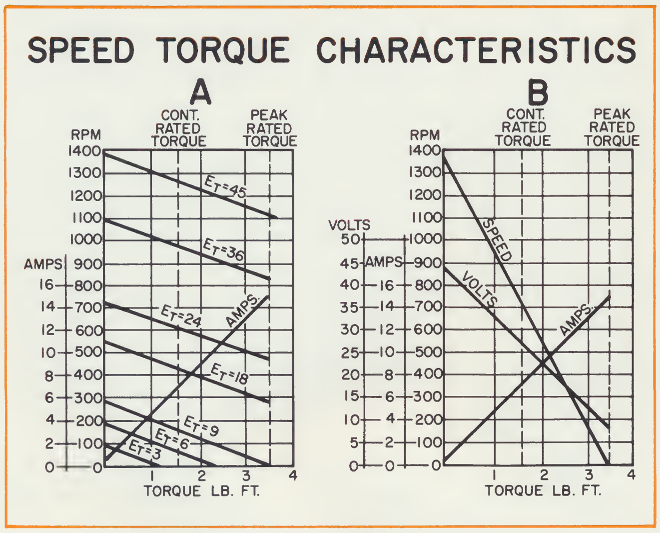

Figure 4.

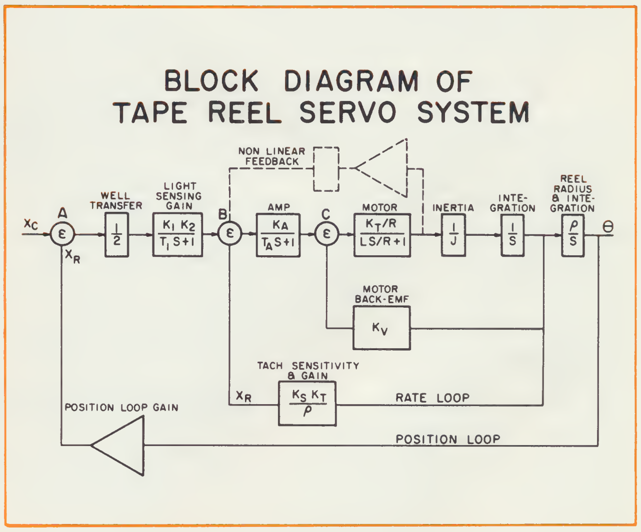

Figure 5.

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motor has an output voltage proportional to speed. If this were fed back to the summing point "B", while it would tend to act as a speed control on the reel, it would run at some speed unrelated to tape speed. This would not maintain the tape position in the well and wide variations would result demanding excessive accelerations to correct. Therefore, the rotary motion on the reel must be converted into linear motion of the tape as it is fed over the capstans. Sylvania placed a series of fiber optics above the buffer wells which are located in such manner that they sense the tape radius as it is played off or taken up on their respective reels. The signal thus created is incorporated in the rate loop where it modifies the output from the tach-generator to the proper value for the tape radius. The resultant output of this loop is then fed back to the summing point "B", where it is summed against the position error signal and fed through another summing point "C", into the motor with the proper magnitude and polarity to control it.

Any sudden change in tape speed, such as a command to stop or reverse, would immediately create a large position signal. In turn, this would apply high voltage to the motor and cause excessive acceleration which could result in tape damage. Here advantage is taken of the torque-current transducer characteristic mentioned earlier. Since acceleration is caused when there is an excess of torque over that required to overcome resisting torques, and since torque is a function of current, a non-linear loop which senses excess current is fed back to summing point "C" in opposition to the resultant signal being fed in from the position and rate loops. This reduces the input to the motor and limits the acceleration to a safe value.

This description has covered how the loop functions and controls for high speed tape operation. This transport must also operate 1/150 of this tape speed — instead of 100 inches per second, $\frac{2}{3}$ of an inch per second. Since the reel speed is slaved to the capstan, its speed adjusts to the new tape speed by reacting with a smaller position error. The voltage applied to the motor terminals through the servo loop decreases to the proper value even though the reel speeds now are approximately 4 rpm and $1\frac{1}{4}$ rpm for the empty and full reels respectively. No adjustments are required and the transport functions as described above. The same holds true for fast rewind where the capstans speed is twice normal high speed operation.

DYNAMIC BRAKING

One remaining feature associated with the use of the direct drive DC motor in this application is quick reversal. The tape must stop and reverse in 6 milliseconds and the position of the tape in the buffer wells reverses concurrently. To keep acceleration within safe limits, the reel drive motors must be reversed in 200 milliseconds. Significantly greater or less time could cause the system to malfunction. Dynamic braking is employed. This is shown schematically in Figure 6, where for simplification, the electronics have been eliminated. Both reel motors at the instant before reversal are connected essentially as shown in "A". At the instant the transport receives a command to reverse, it is reconnected as shown in "B". Here both motors are connected in series, act as generator, and dissipate the small amount of stored energy of the motor and reels by dynamically braking each other. This is one of the capabilities of a DC motor which is not possessed by an AC motor and the low stored energy of the direct drive makes it even better. These are braked with limited current to prevent excessive deceleration which can be as damaging as excessive acceleration. When the motors come to rest, the polarity is applied in the opposite direction as shown in "C" to obtain reversed rotation and the transport operates as before.

This method significantly reduces the power consumed during this operation (one of the requirements for this transport). By simply reversing the polarity on the motors at the time of reversal, approximately 100 watts are required. This power saving helps to reduce the size of the electronic components.

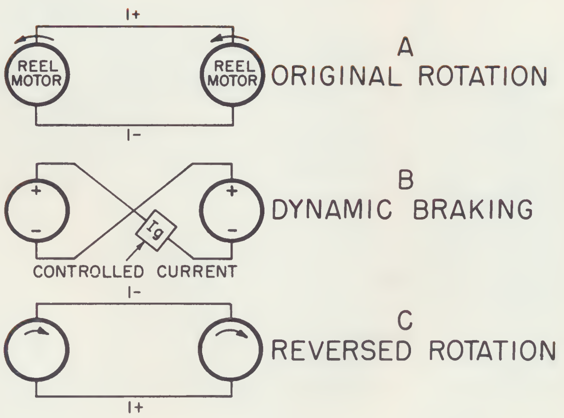

Figure 6.

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